FRC LIFETIME STUDIES FOR THE FIELD REVERSED CONFIGURATION HEATING EXPERIMENT (FRCHX)*

C. Grabowski, J. H. Degnan, D. J. Amdahl, R. Delaney, M. Domonkos, F. M. Lehr, R. Magallanes, P. R. Robinson, E. L. Ruden, W. White, H. Wood
Air Force Research Laboratory
Kirtland AFB, NM 87117-5776 USA

D. Gale, M. Kostora, J. McCullough, W. Sommars
Science Applications International Corporation
Albuquerque, NM 87106 USA

M. H. Frese, S. D. Frese, J. F. Camacho, S. K. Coffey, V. Makhin
NumerEx, LLC
Albuquerque, NM 87106 USA

T. P. Intrator, G. A. Wurden, J. Sears, P. J. Turchi, W. J. Waganaar, T. Weber
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

R. E. Siemon, S. Fuelling, B. S. Bauer
University of Nevada
Reno, Reno, NV 89557 USA

A. G. Lynn, N. F. Roderick
University of New Mexico
Albuquerque, NM 87131 USA

Abstract

The goal of the Field-Reversed Configuration Heating Experiment (FRCHX) is to demonstrate magnetized plasma compression and thereby provide a low cost approach to high energy density laboratory plasma (HEDLP) studies, which include such topics as magneto-inertial fusion (MIF). A requirement for the field-reversed configuration (FRC) plasma is that the trapped flux in the FRC must maintain confinement of the plasma within the capture region long enough for the compression process to be completed, which is approximately 20 microseconds for FRCHX. Current lifetime measurements of the FRCs formed with FRCHX show lifetimes of only 7 ~ 9 microseconds once the FRC has entered the capture region.

A description of the pulsed power systems that comprise FRCHX will be presented along with an overview of the magnetic and plasma diagnostics fielded on the experiment. Results from recent FRCHX experiments will then be presented, and possible reasons for the lifetime limitations will be discussed along with several approaches for overcoming these limitations.

I. INTRODUCTION

The Air Force Research Laboratory (AFRL) and Los Alamos National Laboratory (LANL) are collaborating on an FRC experiment that has the goal of compressively heating plasma in an FRC for the purpose of carrying out HEDLP studies. Included in these plasma studies are such varied topics as magneto-inertial fusion; particle transport within highly magnetized, dense plasmas; plasma instabilities; and neutron interactions with materials. Compact toroids such as the FRC or spheromak are ideal for studies such as these, as they can be translated (e.g., from a formation region to a capture/observation region or a compression region), and their magnetic field topologies help to insulate the hot, dense plasma within the toroid from the low-temperature impurities outside of it [1].

* Work supported by the US Dept of Energy Office of Fusion Energy Studies under IA DE-AI02-04ER54764.

978-1-4577-0631-8/11/$26.00 ©2011 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2011	**N/A**	**-**

4. TITLE AND SUBTITLE
FRC Lifetime Studies For The Field Reversed Configuration Heating Experiment (FRCHX)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory Kirtland AFB, NM 87117-5776 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013, The original document contains color images.

14. ABSTRACT
The goal of the Field-Reversed Configuration Heating Experiment (FRCHX) is to demonstrate magnetized plasma compression and thereby provide a low cost approach to high energy density laboratory plasma (HEDLP) studies, which include such topics as magneto-inertial fusion (MIF). A requirement for the field-reversed configuration (FRC) plasma is that the trapped flux in the FRC must maintain confinement of the plasma within the capture region long enough for the compression process to be completed, which is approximately 20 microseconds for FRCHX. Current lifetime measurements of the FRCs formed with FRCHX show lifetimes of only 7 ~ 9 microseconds once the FRC has entered the capture region. A description of the pulsed power systems that comprise FRCHX will be presented along with an overview of the magnetic and plasma diagnostics fielded on the experiment. Results from recent FRCHX experiments will then be presented, and possible reasons for the lifetime limitations will be discussed along with several approaches for overcoming these limitations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**6**	

Figure 1 shows an illustration of the basic structures and geometry of the FRCHX. In the experiment, the FRC is formed by a reversed-field theta pinch on an already

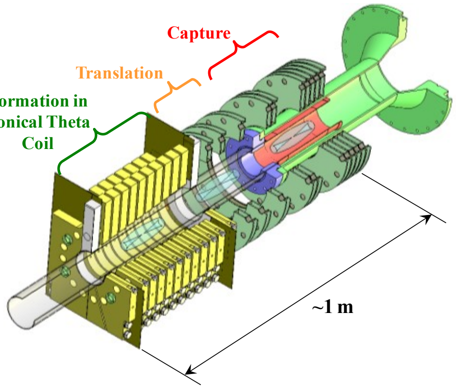

Figure 1. The basic layout for FRCHX.

magnetized plasma inside a quartz tube. A conical bore inside the Theta (pinch) coil also enables the FRC to be ejected as it is being formed. Both Guide and Mirror fields that are set up prior to formation then allow the FRC to be translated across a short distance into a capture region where it is stopped. The final compression heating of the FRC plasma is carried out by imploding an aluminum shell (liner) around the trapped FRC. Due to the destructive nature of these compression heating tests, several hundred tests will be performed without compression to study and characterize the FRCs before a compression heating test is finally undertaken.

Desired values for FRC plasma density and temperature after formation are ~10^{17} cm^{-3} and 200-300 eV, respectively [2]. These values are targeted in experiments by adjusting the deuterium pre-fill pressure in the vacuum vessel before formation and by appropriate timings and amplitudes for the various magnetic fields. Based upon computational results, densities and temperatures of this order within the FRC should enable densities and temperatures of ~10^{19} cm^{-3} and several keV, respectively, to be achieved during the liner compression.

This paper outlines the issues that have been encountered on FRCHX related to the trapped-flux lifetime of FRC once it has come to rest in the capture region. This lifetime must be sufficiently long so that the FRC will persist until the liner implosion reaches stagnation on axis, which is approximately 25 µs after the start of the current drive and at which point the maximum compression of the FRC will be achieved. Experimental results to date have shown the longest FRC lifetimes to be at most just half of the time needed after they are captured. Section II begins by providing an overview of the FRCHX pulsed power systems. The experiment diagnostics are also described. Section III then discusses some of the recent results that illustrate these shorter-than-desired lifetimes. Approaches to extend the lifetime, both implemented and soon to be implemented, are outlined here. Section IV summarizes the experimental results to date and the upcoming tests planned.

II. OVERVIEW OF FRCHX

A. Experimental Apparatus

A diagram of the FRCHX magnetic field coils is shown in Fig. 2. FRC formation takes place within the 10-segment, single-turn Theta coil. There are three independent capacitor banks that drive this coil as part of the formation process: a Bias bank, built from two 2.5-mF modules, a Pre-ionization (PI) bank, consisting of a single 2.1 µF capacitor, and a Main bank comprised of two 72-µF capacitor assemblies that are physically stacked one on the other and that are marxed when discharged (a re-configured Shiva Star bank module). The Main bank current is crowbarred when its peak current is reached. The Bias bank, which is the first of the formation banks to be triggered, is isolated from the higher-voltage Main and PI banks by a high-impedance (isolation) inductor. Single-turn Cusp coils above and below the Theta coil aid with magnetic reconnection during the formation process, and two additional 1.5-mF banks drive these coils.

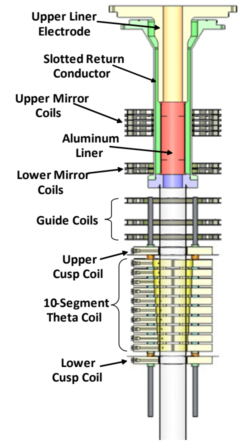

Figure 2. Cross-sectional diagram of the FRCHX coil assembly.

To guide the FRC from the formation region to the capture region and the solid liner, three multi-turn Guide coils were positioned along the short translation section between these two regions. A magnetic mirror at the bottom of the capture region is set up by two additional multi-turn coils, and three more multi-turn coils establish an upper magnetic mirror above the capture region. All eight of these coils are connected in series and are driven by a 12-mF capacitor bank. Such a large bank capacitance is necessary in order to drive the field coils for a sufficient amount of time ($t_{1/4}$ ~ 4.7 ms) to allow the mirror fields to diffuse through the solid liner and its electrodes. The outer return conductor for the solid liner has been slotted to make it almost transparent to these fields [3]; otherwise an even longer diffusion time would be required.

The Shiva Star high-energy capacitor bank is a seventh bank for FRCHX when compression heating tests are performed. The Shiva bank is comprised of thirty six 36-µF bank modules, and the bank delivers 11 ~ 12 MA of current to drive the liner implosion around the FRC [4,5].

B. The FRC Formation Process

Figure 3 illustrates how the FRC plasma and field structure is formed. First, a Bias field is set up in the theta coil. Then Upper and Lower Cusp fields are applied at either end while the Bias field is still ramping up. When both the Cusp and Bias fields have peaked, a low-pressure (10 ~ 100 mTorr) D_2 background gas in the vacuum

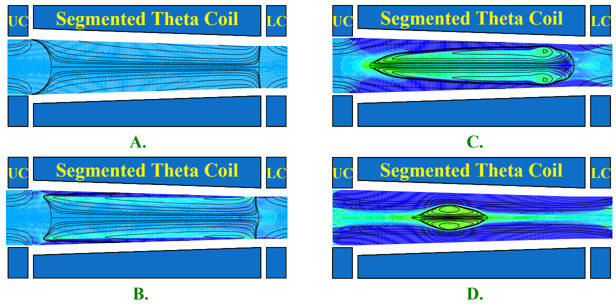

Figure 3. The FRC formation sequence: A. Bias and Cusp fields are applied; pre-fill gas is ionized. B. Main field is applied. C. Field lines reconnect. D. Plasma contracts; beginning of motion into translation region.

vessel is ionized by applying the high-frequency (~ 230 kHz) ringing PI field to the Theta coil. The Main field, which is oriented opposite to the Bias field, is then applied to compress the plasma that was just formed.

As the plasma is being compressed, the inner field lines of the Main field tear and reconnect with the Bias field lines from the core of the plasma at each end, while at the same time the plasma now begins to move toward the larger end of the Theta coil due to the $J_r \times B_\Theta$ forces. The newly formed FRC continues to contract inward on itself until reaching equilibrium while its momentum directed towards the end of the Theta coil continues to increase.

Due to the slow rise time, the Guide and Mirror field discharge begins ~6 ms before the formation process begins. Furthermore, due to the short trapped flux lifetimes presently exhibited by the FRCHX FRCs the Shiva Star current discharge is begun before formation is completed. Figure 4 shows a timeline of when the various FRCHX banks are triggered.

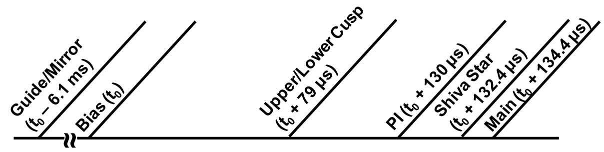

Figure 4. Timeline for triggering the FRCHX banks.

C. Diagnostics

Magnetic and optical diagnostics have been positioned in the formation, translation, and capture regions of FRCHX to characterize the plasma and the magnetic field topology surrounding it. The quartz tube, which serves as the vacuum vessel in the formation and much of the translation regions provides easy access for the optical diagnostics; in the remainder of the translation region and in the capture region other accommodations must be made (e.g., access ports in the structures, or, in the capture region, observation or insertion of probes from above).

Among the magnetic and optical diagnostics fielded are magnetic pick-up loops, flux loops, and fiber optic light monitors. Signals from the pick-up loops provide information about magnetic field profile in the experiment and FRC location, and when processed with the flux loop signals the two provide an estimate of the maximum radius of the FRC's closed field lines (i.e., the excluded flux radius). Open-ended, unfiltered optical fibers at various locations on the experiment show when the D_2 first breaks down and afterwards show where plasma is present. By comparing signals from multiple fibers, time-of-flight information can be obtained.

To measure the plasma density a four-chord HeNe laser interferometer has been set up. To enable measurements at multiple axial locations as well as to protect the expensive optical hardware during compression heating tests, the probe beams are conveyed between the optical table and the experiment by fiber-optic cables [6]. Multiple probe beams can be set up along various chords at a single axial location to map out the FRC radial density profile or they can be positioned along the diameter at different axial locations to provide a line-averaged density along with time-of-flight information.

End-on diagnostics have included time-gated cameras, optical spectroscopy, and filtered x-ray diodes. The latter two have also been fielded radially just below the solid liner. The time-gated cameras are used to record visible light images of the plasma, which provide some indication of plasma structure and dynamics. Plans and hardware are being developed to record images in the VUV spectrum, as these will provide a view of the hotter regions of the plasma. The spectrometers in use are set up remote from the experiment, and light is brought to the spectrometer via large cross-section quartz optical fibers. Information obtained from the spectrometers is used to help identify colder region impurities. The filtered x-ray diodes are fielded in the same locations as the spectrometer fibers and are used to estimate temperature, density product, and impurities in hotter regions.

A diagnostic that has been designed and fielded for the purpose of detecting plasma instabilities is the quadrant probe. The quadrant probes are fielded on the lower port of FRCHX and consist of four diodes or four fibers (that are run to photomultipliers) with collimators in front of them for the purpose of monitoring only a quadrant of the axial view along FRCHX. For an FRC that does not go unstable the signals from all four of the quadrant probes should be approximately the same and should have little variation in time until the FRC decays away. When an FRC does develop an instability, which will cause it to rotate or tilt, one can expect there to be notable differences between the signals coming from the four probes and for them to have much more variation as a function of time.

III. ANALYSIS OF FRC LIFETIME

In the spring of 2010 the first integrated engineering test of all of the FRCHX systems, including the Shiva Star bank to drive a liner implosion was performed. All bank trigger timings and current deliveries were as intended, and a radiography image collected during the implosion showed the liner to be maintaining uniformity. The test could have also served as the first FRC compression heating test, however it was already known at that time, from earlier tests with an extended quartz tube in place of the liner, that FRC lifetimes were too short to last through the duration of the liner implosion.

Subsequent tests with a mock-up of the liner, its electrodes and the return conductor around them, have focused on trying to identify the reasons for the shortened lifetime and to take steps to extend it. Possible reasons for a shortened FRC lifetime include poor formation, an incorrectly configured (too shallow) magnetic well between the two sets of mirror coils, and late-time instabilities. Avenues that have recently been explored to attempt to extend the FRC lifetime are better tuning of the bank parameters through systematic parameter scans, the use of RF pre-pre-ionization to partially ionize the gas in advance of the PI bank discharge, and implementation of a passive rotation control scheme to delay the onset of anticipated rotational instabilities. Several more approaches to improve lifetime to be implemented in the near future include the use of gas puffing instead of a static pre-fill (so that the translating FRC is not cooled by having to push through the background gas between the formation and capture regions), active rotation control schemes, redesigning the Mirror coils to improve the well profile, and implementing multi-pole fields around the formation and/or capture regions.

Before beginning this campaign, the upper electrode of the mock liner assembly was modified to allow integrated B-dot probes to be inserted into the liner from above near its walls. This was done in order to be able to directly measure the FRC lifetimes once they had been captured between the magnetic mirrors. Figure 5 shows a typical set of waveforms recorded from these B-dot probes during a formation and capture-only test that illustrates the lifetime problem. The locations of the four probes whose signals are presented in this graph are as follows: "T0" is just above the Upper Cusp coil; "T3" is at the peak of the lower mirror field; "T4" is in the center of the

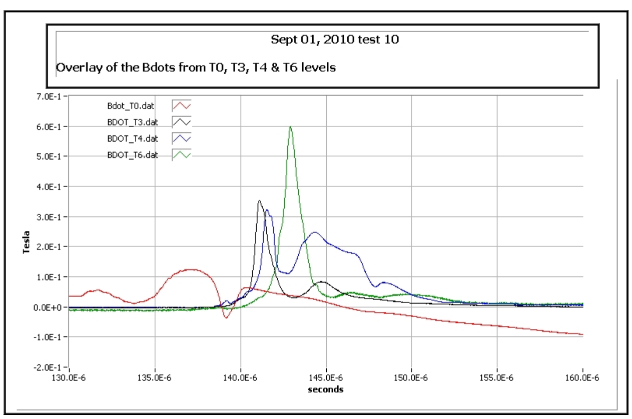

Figure 5. Translation and capture region B-dot signals for a test with the following bank charge and pre-fill parameters: Main: ±35 kV; PI: 65 kV; Bias: 5.6 kV; L. Cusp: 2.4 kV; G/M: 3.2 kV; Pre-fill: 50 mTorr.

capture region; and "T6" is a short distance above the peak of the upper mirror. The slow background fields from the Guide and Mirror coils have been ignored, thereby allowing the baselines of the T3, T4, T6 B-dot probes to be placed at 0 so that the relative signals from each probe due to the FRC can be better seen. Because the T0 B-dot probe is just above the Upper Cusp coil, it picks up the faster field variations due to the PI and Main bank discharges and thus does not have a very flat baseline. The influence of the FRC can be seen, however, as the negative impulse appearing at ~139 μs.

The FRC can thus be seen passing T0 at ~139 μs, T3 at ~141.5 μs, and T4 at 142 μs. The T6 signal has a strong peak at ~143 μs, indicating that the FRC is stretching past the upper mirror, but it appears to be pulled back into the capture region, as secondary peaks are observed on the T4 and T3 signals at ~144 μs and ~145 μs, respectively. The T4 signal undergoes a much slower decay after its second peak than it did after its first, suggesting that the FRC is coming to rest in the magnetic well, however the lifetime after capture is rather short, as the T4 signal persists for only 3~4 μs following the second peak. The time between the start of the Shiva Star discharge current and the stagnation of the solid liner on axis is ~25 μs; taking into account both the timeline in Fig. 4 and the waveforms in Fig. 5, it becomes apparent that the FRC lifetime needs to be ~11 μs or more longer in duration than it is.

The following sub-sections elaborate on the three avenues mentioned above for extending FRC lifetime and the experimental results obtained thus far when implementing them.

A. Bank Parameter Scans

The following bank parameter variations were considered: a) raising the mirror fields to reduce the stretching of the FRC (and possible loss of mass) beyond the upper mirror; b) varying the Bias field, which according to traditional lore a greater Bias field should lead to greater trapped flux and therefore longer lifetime, however the proper Bias field may be dependent upon pre-fill pressure and thus lower Bias fields may be warranted; c) raising the Main field, with the Bias field held constant, to determine if the Main-to-Bias field ratio is an important factor in FRC formation (a higher Main field would also ensure FRC gets pushed past the lower Mirror as the Guide and Mirror fields are raised); and d) varying the extent to which the PI field nulls out and exceeds the Bias field (the "zero crossing"), as this should affect the ionization dynamics.

Tests in which the Mirror (and Guide) fields were raised (up to 38% higher than the values used in the first integrated systems test) have led to noticeable improvements in the shape and amplitudes of the B-dot waveforms, specifically the T4 B-dot waveforms. It is assumed that since the stronger lower mirror reduces the velocity of the FRC, it bounces less once it is inside the capture region, and the stronger upper mirror then suppresses stretching of the FRC (and assumed resultant particle loss) beyond the upper mirror. Despite these encouraging signs, there were no noticeable improvements to FRC lifetime, though.

Initial scans in which the Bias field was varied showed that further increases in the amplitude of the T4 B-dot waveform could be obtained with increasing Bias field, and an incremental increase in the lifetime (~1 μs) was now observed. In keeping with the notion that it may be necessary to reduce the Bias field for the pre-fill pressures being used, further incremental increases in lifetime were observed during tests in which one module of the Bias bank fired late or not at all due to problems with its ignitron. Figure 6 shows the set of waveforms from one of these tests. As can be seen, the lifetime (approximated by the FWHM of the T4 B-dot signal) is now approaching 8

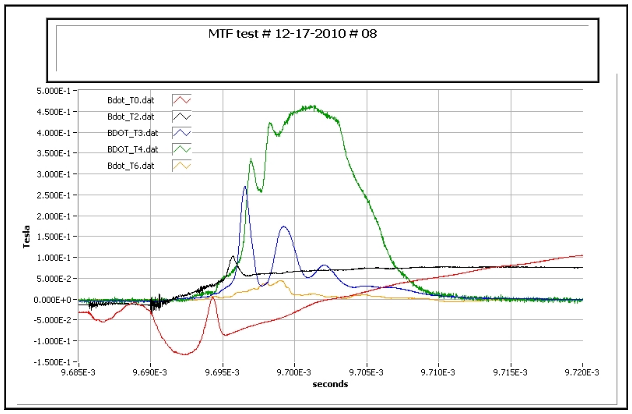

Figure 6. B-dot signals for a test with the following bank charge and pre-fill parameters: Main = 70 kV; PI = 65 kV; L. Cusp = 2.4 kV; G/M = 4.4 kV; Bias = 4.7 kV, though only one module fired; Pre-fill: 50 mTorr.

μs, and the signal has become much squarer in appearance. This finding prompted several sets of tests in which the Bias charge voltage was lowered or only one module of the bank was charged and fired. Interestingly, the lifetimes and appearance of theT4 B-dot signals in these tests were much like those obtained during the scans with the full Bias bank. Line integrated densities measured with the interferometer in the formation and translation regions showed that the density profiles all stayed about the same, as well, with the peak densities in the formation region being 1.7 ~ 2.3 x 10^{17} cm^{-2} and those just below the liner being 1.1 ~ 1.4 x 10^{17} cm^{-2}. This finding suggests that regardless of the amount of Bias flux available only a certain amount is being trapped in the FRC during formation.

Thus far, only limited scans of the Main bank voltage have been performed, and results have showed no change in FRC lifetime. Scans of the PI zero-crossing have been limited, as well, and have been limited to tests performed with the RF source that are discussed in the next section.

B. RF "Pre-Pre-Ionization"

It has been noted that during the formation process when using a ringing PI bank to breakdown the gas, the breakdown usually occurs near the time at which the PI discharge has nulled out the Bias field (Fig. 7). Fiber optic light monitors on FRCHX have shown this to be true for this experiment, as well. This is somewhat counter-

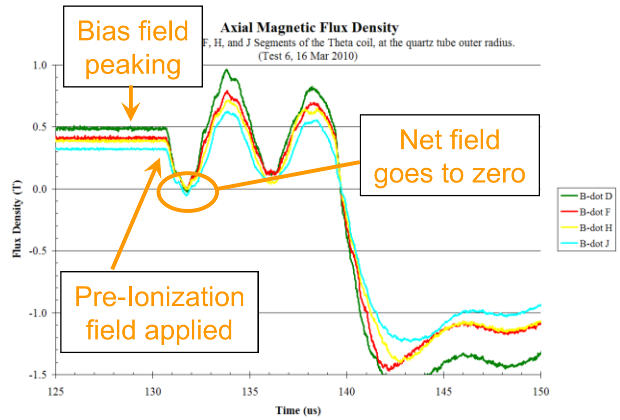

Figure 7. B-dot probe waveforms, showing how the net B field goes to zero during FRC formation.

intuitive, as the electric field is highest when dB/dt is the greatest (at the start of the PI discharge), however the Bias field appears to insulate against breakdown at this time, and thus breakdown is only able to occur as the Bias field is reduced to zero by the PI field.

Unfortunately, if the gas breaks down at this time, then there is essentially no background magnetic field to be imbedded in the plasma, and the scenario illustrated in Fig. 3 is not entirely accurate. That FRCs are formed, however, is verified by interferometery and by calculation of an excluded flux radius from the B-dot and flux loop data. It is concluded that some diffusion of the magnetic field into the plasma occurs as the PI field continues its cycle and begins to add to the background Bias field.

The use of an RF source to assist with the ionization is largely motivated by the desire to reduce the PI bank discharge current so that the Bias field is not as drastically reduced and yet still obtain adequate ionization. Unfortunately, the use of RF to improve FRC parameters in previous experiments is not well documented. The initial approach for FRCHX has been to apply the RF electric fields radially (perpendicular to the Bias field) through the use of two rectangular copper electrodes that are pressed up against the quartz tube in the formation region. The foils were potted in nylon tube using a silicone encapsulant and the assembly spanned approximately 80% of the formation region.

Initial tests with the RF pre-pre-ionization system have been somewhat promising. The RF is applied before the Guide and Mirror coil bank is triggered. There is therefore a low-level glow discharge inside the quartz tube before the Bias field is applied. The PI and Main banks are triggered at their normal times, and it has been possible to reduce the PI bank charge voltage by almost 25% (from 65 kV to 49 kV) and still form and translate an FRC.

The T4 B-dot signals are not as strong with these parameters, and there has been no indication of increased lifetime, so the next iteration in the pre-pre-ionization system design is to mismatch the electrode impedance with respect to the RF source impedance in order to increase the amplitude of the RF electric fields. The electrode configuration is also being changed: two rings are being used, one at the top of the formation region and one at the bottom, instead of the rectangular electrodes in an effort to apply the electric fields parallel to the Bias field. The RF will also be switched on rapidly in an effort control exactly when the gas breaks down due to the RF.

C. Passive Rotation Control

A part of the recent experimental campaign has been devoted to testing concepts that will suppress or mitigate instabilities such as the n = 2 when they start to develop. The first of these concepts is a means of passively suppressing end shorting [6] of the axial magnetic field lines and entails ensuring that the magnetic field lines running the length of FRCHX terminate on a dielectric surface so that electric fields perpendicular to these field lines are not shorted out at these boundaries. The fields below the Lower Cusp coil already terminate on the quartz tube. Above the liner it was necessary to slide a dielectric sleeve into the bore of the liner's upper electrode to set up these same boundary conditions there. Because of availability, a Teflon sleeve was used initially to test the concept, and later, when it was possible to do so, the Teflon sleeve was with a quartz sleeve.

Using the same bank charge and timing parameters that were used for the first integrated FRCHX engineering test, a number of tests were performed with each of the sleeves in place, and the results were compared to those from earlier tests in the campaign without a sleeve. The comparison is shown in Fig. 8. The red T4 B-dot waveforms are from tests with no dielectric sleeve, the green and blue waveforms are from tests with the Teflon sleeve, and the orange waveform is from the one test with identical parameters with the quartz sleeve.

There are noteworthy improvements in the T4 B-dot pulse shape and amplitude after the insertion *either*

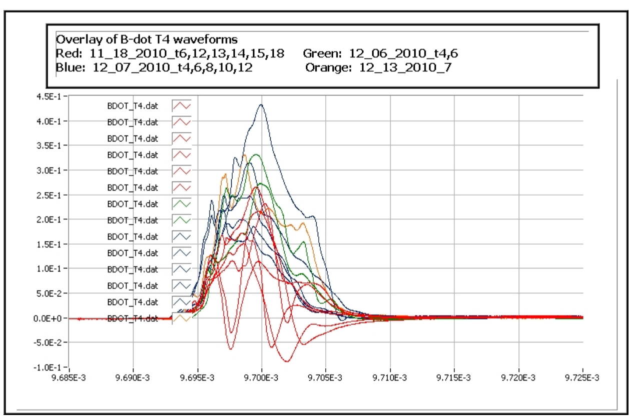

Figure 8. T4 B-dot signals for tests with and without the dielectric sleeves. Bank charge and pre-fill parameters are as follows: Main: ±35 kV; PI: 65 kV; Bias: 5.6 kV; L. Cusp: 2.4 kV; G/M: 3.2 kV; Pre-fill: 50 mTorr.

sleeve. Improvements of this order are similar to those that were observed after increasing the Guide and Mirror fields. Slight increases in pulse width are also observed.

IV. SUMMARY

With the successful integrated engineering test of the FRCHX systems in the spring of 2010, the only remaining milestone that must be met before performing the first FRC compression heating test is extending the FRC trapped-flux lifetime. The tests performed throughout this current experimental campaign have led to notable improvements in the magnitude of the trapped flux and the behavior of the FRC once it enters the capture region, but thus far only very modest improvement in lifetime have been observed.

The FRCHX experimental campaign will now be concentrating on the parameter scans that have not yet been completed and on characterizing the new RF pre-pre-ionization system and the FRCs formed with it. In addition, efforts will now be directed toward implanting many of the other approaches to improving lifetime that were mentioned earlier (e.g., gas puffing, active rotation control, and possibly redesigning the Mirror coils to improve the well profile).

VI. REFERENCES

[1] M. Tuszewski, "Field Reversed Configurations," Nucl. Fusion, vol. 28, pp. 2033-2092, 1988.

[2] G. A Wurden, T. P. Intrator, S. Y. Zhang, et. al., "FRC Plasma Studies on the FRX-L Plasma Injector for MTF," Proceedings of the 20th IAEA Fusion Energy Conference, IC/P6-53, 2004.

[3] M. Domonkos, D. Amdahl, J. Degnan, et. al., "Guide and Mirror Magnetic Field Diffusion Calculations for the FRC Compression Heating Experiment (FRCHX) at AFRL," Bulletin of the Am. Phys. Soc., vol. 52, no. 11, PP8.109, 2007.

[4] J. H. Degnan, D. Amdahl, A. Brown, et. al., "Experimental and Computational Progress on Liner Implosions for Compression of FRCs," Trans. Plasma Sci., vol. 36, pp. 80-91, 2008.

[5] J. H. Degnan, P. Adamson, D. Amdahl, et. al., "Field Reversed Configuration (FRC) formation and compression," to appear in the Proceedings of Megagauss 13 Conference, 2010.

[6] J. F. Camacho, A. G. Lynn, and E. L. Ruden, "Visibility Measurements on a Fiber-Optic Probe Interferometer System," Bulletin of the Am. Phys. Soc., vol. 54, no. 15, TP8.147, 2009.

[7] L. C. Steinhauer, "End-Shorting and electric field in edge plasmas with application to field-reversed configurations," Phys. Plasmas, vol. 9, pp. 3851, 2002.